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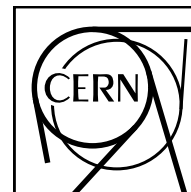
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Measurement of the W boson polarization in top quark decays with the ATLAS detector

The ATLAS Collaboration

Abstract

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Measurement of the W boson polarization in top quark decays with the ATLAS detector

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ABSTRACT: This paper presents measurements of the polarization of W bosons in top quark decays, derived from $t\bar{t}$ events with missing transverse momentum, one charged lepton and at least four jets, or two charged leptons and at least two jets. Data from pp collisions at a centre-of-mass energy of 7 TeV were collected with the ATLAS experiment at the LHC and correspond to an integrated luminosity of 1.04 fb^{-1}. The measured fractions of longitudinally, left- and right-handed polarization are $F_0 = 0.67 \pm 0.07$, $F_L = 0.32 \pm 0.04$ and $F_R = 0.01 \pm 0.05$, in agreement with the Standard Model predictions. As the polarization of the W bosons in top quark decays is sensitive to the Wtb vertex Lorentz structure and couplings, the measurements were used to set limits on anomalous contributions to the Wtb couplings.

KEYWORDS: top quark, W boson polarization, anomalous Wtb couplings

Contents

1 Introduction

Discovered in 1995 by the CDF and DØ experiments [1, 2], the top quark is the heaviest known fundamental particle, with a mass of 173.2±0.9 GeV [3]. Measurements of top quark properties play an important role in testing the Standard Model and its possible extensions. One particular test is the study of the Wtb vertex Lorentz structure and couplings, which can be probed by measuring the polarization of W bosons produced in top quark decays.

At the LHC, top quarks are produced mainly in pairs via the strong interaction and are predicted to decay via the electroweak interaction into a W boson and a bottom quark with a nearly 100% branching fraction. Events with $t\bar{t}$ pairs can thus be classified according

to the decay of the two produced W bosons. Each boson can decay either into a quark-antiquark pair or into a charged lepton and a neutrino. The single-lepton and dilepton topologies, both considered in the analyses presented in this paper, have one and two isolated charged leptons in the final state. Only electrons and muons, including those from τ decays, are considered here.

The Wtb vertex is defined by the electroweak interaction and has a $(V - A)$ structure where V and A are the vector and axial-vector contributions to the vertex. Since the W bosons are produced as real particles in top quark decays, their polarization can be longitudinal, left-handed or right-handed. The fractions of events with a particular polarization, F_0, F_L and F_R, are referred to as helicity fractions. They are predicted in next-to-next-to-leading-order (NNLO) QCD calculations to be $F_0 = 0.687 \pm 0.005$, $F_L = 0.311 \pm 0.005$, $F_R = 0.0017 \pm 0.0001$ [4]. These fractions can be extracted from measurements of the angular distribution of the decay products of the top quark. The angle θ^* is defined as the angle between the momentum direction of the charged lepton from the decay of the W boson and the reversed momentum direction of the b-quark from the decay of the top quark, both boosted into the W boson rest frame [5]. The angular distribution is:

$$\frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4} \left(1 - \cos^2\theta^*\right) F_0 + \frac{3}{8} \left(1 - \cos\theta^*\right)^2 F_L + \frac{3}{8} \left(1 + \cos\theta^*\right)^2 F_R. \qquad (1.1)$$

All previous measurements of the helicity fractions, performed by the CDF and DØ Collaborations [6–8] at the Tevatron, are in agreement with Standard Model predictions.

Information about the polarization of the W bosons can also be obtained through complementary observables, such as the angular asymmetries, A_+ and A_-, defined as:

$$A_\pm = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)}, \qquad (1.2)$$

with $z = \pm(1 - 2^{2/3})$ for $A_\pm$, allowing the dependence on F_L and F_R to cancel, respectively. The asymmetries can be related to the helicity fractions by a simple system of equations [9, 10]. In the Standard Model, the NNLO values for these asymmetries are $A_+ = 0.537 \pm 0.004$ and $A_- = -0.841 \pm 0.006$ [4].

In the presence of anomalous Wtb couplings the helicity fractions and angular asymmetries depart from their Standard Model values [5, 10]. In effective field theories, dimension-six operators can be introduced which modify the Wtb vertex [11–13]. Coefficients controlling the strength of these operators can be constrained by measurements of the helicity fractions or the angular asymmetries.

This paper describes measurements of the W boson polarization in top quark decays and the constraints on the Wtb vertex structure based on a data set recorded with the ATLAS detector between March and June 2011 and corresponding to an integrated luminosity of 1.04 fb^{-1}. The helicity fractions were measured using two different methods. The first compares the observed $\cos\theta^*$ distribution with templates for different W boson helicity states obtained from simulation. The second method extracts angular asymmetries from an unfolded $\cos\theta^*$ spectrum corrected for background contributions. Limits on anomalous couplings, generated by the aforementioned dimension-six operators, were set using the combined result from the two measurements.

This paper is structured as follows. Data samples and simulated samples modelling signal and background processes are described in Section 2, followed by a summary of the event selection in Section 3. The analysis strategies can be found in Section 4. Sources of systematic uncertainty are discussed in Section 5, the results are summarized in Section 6 and Section 7 concludes the paper.

2   Data and simulation samples

The ATLAS detector [14] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating three large superconducting toroid magnet assemblies. A three-level trigger system, designed to reduce the event rate from 40 MHz to about 200 Hz, is used to select events of interest.

2.1   Data sample

Data from pp collisions at a centre-of-mass energy of 7 TeV were collected using single-lepton triggers with transverse momentum thresholds of 20 GeV for electrons and 18 GeV for muons. The size of the data sample corresponds to an integrated luminosity of 1.04 ± 0.04 fb^{-1} [15, 16].

2.2   Signal and background modelling

Signal and most background processes were modelled by Monte Carlo (MC) simulation. The signal process was simulated using two different generators. The leading order (LO) Monte Carlo generator PROTOS [10, 17] was used with the CTEQ6L1 sets of parton distribution functions (PDFs) [18] to generate three samples assuming $F_0 = 1$, $F_{\mathrm{L}} = 1$ and $F_{\mathrm{R}} = 1$. This was achieved by choosing appropriate values for anomalous Wtb couplings, as described in Refs. [9, 10]. The output was interfaced to PYTHIA [19] to simulate parton showers and hadronization. In addition, the next-to-leading-order (NLO) generator MC@NLO [20–22] was used with the CTEQ6.6 PDF set [23] for studies of systematic differences in the top quark production and decay modelling.

The W and Z boson production in association with multiple jets was simulated using the ALPGEN generator [24] and the CTEQ6L1 PDF set. Tree-level matrix elements with up to five final-state partons were included. The standard ALPGEN matching scheme was used to remove overlaps between the n and $n + 1$ parton samples. Heavy flavour samples containing $Wb\bar{b}$, $Wc\bar{c}$, Wc and $Zb\bar{b}$ events were simulated separately. The Z+jets samples were generated with dileptons in the invariant mass range $10 < m_{\ell\ell} < 2000$ GeV. Diboson processes were simulated using HERWIG [25]. Single top quark production was simulated using MC@NLO, invoking the 'diagram removal scheme' [26] to remove overlaps between the single top quark and $t\bar{t}$ final states. An additional sample of W+jets events was generated with SHERPA [27] and used to study systematic uncertainties. Details are described in Section 5. Apart from the PROTOS $t\bar{t}$ samples, all events were hadronized with

HERWIG using JIMMY [28] for the underlying event model. Different underlying event tunes were used, depending on the hadronisation program used (*i.e.* PYTHIA or HERWIG) [29].

Additional MC samples were used for the evaluation of systematic uncertainties. These were generated with the ACERMC [30] and POWHEG [31, 32] generators interfaced to PYTHIA for hadronization. They are described in Section 5. A top quark mass of 172.5 GeV was assumed for all signal samples if not stated otherwise. Additional MC@NLO samples were generated assuming different top quark masses.

All simulated events contain multiple *pp*-interactions and contain pileup contributions corresponding to a bunch spacing of 50 ns. These simulated events were re-weighted such that the average number of interactions per proton-proton bunch crossing was the same in data and MC simulation. The average number of interactions per event was roughly six. All samples were processed by the detector and trigger simulation after event generation [33, 34], and subjected to the same reconstruction algorithms as the data.

The cross-section of simulated $t\bar{t}$ samples was normalized to 164.6 pb, the value obtained from approximate NNLO calculations [35–37], and consistent with recent measurements [38]. While the Z+jets normalization was obtained from the NNLO QCD cross-section calculations in the single lepton channels, a data-driven estimate for the normalization was used for the dilepton channels [38]. The diboson with jets production was rescaled to match NLO calculations of the inclusive cross-sections.

For the single-lepton analysis, the multijet production background, where an electron or muon originates from hadron decay or instrumental background, was estimated from data as described in Refs. [39, 40]. The W+jets background was obtained from simulation, except that its normalization was derived from data, from a study of the asymmetry in the production of W^+ and W^- bosons [40]. For the dilepton analysis, background contributions from W+jets, single-lepton $t\bar{t}$ and single top quark production were estimated using the method described in Ref. [38]. In the single-lepton and dilepton analyses this source of background is labelled as "misidentified leptons".

3 Event selection

3.1 Physics object definition

The reconstruction and identification of electrons, muons, jets and the magnitude of the missing transverse momentum ($E_\mathrm{T}^\mathrm{miss}$) used in the analyses presented here followed the criteria employed for the measurement of the $t\bar{t}$ production cross-section [39]. More details, including a description of the trigger and the vertex requirements, can be found in Ref. [40].

The $t\bar{t}$ events with at least one isolated charged lepton (electron or muon) in the final state were considered as signal. Events with τ leptons decaying into muons or electrons in the final state were also considered to be part of the signal.

All the considered events were required to fulfil general event quality criteria and to have a well-defined primary vertex with at least five associated tracks. Reconstructed electrons were required to have $E_\mathrm{T} > 25$ GeV and $|\eta| < 2.47$ excluding $1.37 < |\eta| < 1.52$,

while muons were required to have $p_T > 20$ GeV and $|\eta| < 2.5$ [1]. Jets were reconstructed with the anti-k_t algorithm [41] with a radius parameter equal to 0.4. They were required to have $p_T > 25$ GeV and $|\eta| < 2.5$. For electrons, the energy not associated to the electron cluster but contained in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ around it was required not to exceed 3.5 GeV. For muons, the sum of track transverse momenta and the total energy deposited in a cone of $\Delta R = 0.3$ around the muon were both required to be less than 4 GeV. Muons reconstructed within a $\Delta R = 0.4$ cone of a jet satisfying $p_T > 20$ GeV were removed to reduce the contamination caused by muons from hadron decays within jets. Subsequently, jets within $\Delta R = 0.2$ of an electron candidate were removed to avoid double counting, which can occur because electron clusters are also reconstructed as jets.

A combination of two algorithms was used for b-jet identification (b-tagging). They are based on reconstructed secondary vertices and the impact parameter significances of tracks within jets. The chosen working point resulted in a b-tagging efficiency of 70% for jets originating from b-quarks in a sample of simulated $t\bar{t}$ events and a light-quark jet rejection factor of about 100 [42].

3.2 Single-lepton channels

The single-lepton $t\bar{t}$ signal is characterized by a high-p_T isolated charged lepton and missing transverse momentum from the neutrino, from the leptonically decaying W boson, two light-quark jets from the hadronically decaying W boson and two b-quark jets. The two channels with either an electron or a muon in the final state are referred to as single-electron and single-muon channels. The following event selection requirements were applied:

- the appropriate single-electron or single-muon trigger had fired;

- events were required to contain exactly one isolated electron or muon;

- in the single-electron channel, $E_T^{\text{miss}} > 35$ GeV and $m_T(W) > 25$ GeV were required[2] while in the single-muon channel the criteria were $E_T^{\text{miss}} > 20$ GeV and $E_T^{\text{miss}} + m_T(W) > 60$ GeV;

- events were required to have at least four jets, with at least one of them being tagged as a b-jet.

The numbers of events expected after all selection requirements are shown in Table 1 for the single-electron and single-muon channels, together with the observed numbers of events in the data sample. The single-electron channel contains significantly fewer events than the single-muon channel due to the more stringent requirements on the lepton E_T

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[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

[2]Here $m_T(W)$ is the W boson transverse mass, reconstructed as $\sqrt{2p_T^\ell p_T^\nu [1 - \cos(\phi^\ell - \phi^\nu)]}$ where the measured missing transverse momentum provides the neutrino information.

Table 1. Event yields in the single-electron and single-muon channels after the event selection. The table shows the expected number of events including their estimated total uncertainty as well as the number of events observed in the data sample.

Process	Single electron	Single muon
$t\bar{t}$	4400 ± 1100	6500 ± 1400
W+jets	900 ± 700	1400 ± 1000
Z+jets	120 ± 90	140 ± 90
Diboson	14 ± 12	22 ± 12
Single top	260 ± 90	360 ± 110
Misidentified leptons	220 ± 220	500 ± 500
Total predicted	5900 ± 1300	9000 ± 1800
Data	5830	9121

(p_T), $E_\mathrm{T}^\mathrm{miss}$ and $m_\mathrm{T}(W)$. The observed numbers of events are in agreement with those expected, with purities of 75% and 72% for the single electron and single muon channels. The systematic uncertainty discussed in Section 5 dominates the error on the event yields, with jet energy scale, signal and background modelling, and b-tagging being the dominant sources of uncertainty. Example distributions in data are compared with the Standard Model predictions in Figure 1. The data are described well by the expected distributions.

3.3 Dilepton channels

The dilepton $t\bar{t}$ signal is characterized by two high-p_T isolated charged leptons, missing transverse momentum corresponding to the undetected neutrinos from the two leptonically decaying W bosons, and two b-quark jets. The three channels are referred to as ee, $\mu\mu$ and $e\mu$ channels. The following event selection requirements were applied:

- the single-electron trigger had fired for the ee channel, the single-muon trigger had fired for the $\mu\mu$ channel and either of these triggers had fired for the $e\mu$ channel;

- events were required to contain exactly two oppositely charged and isolated leptons (ee, $\mu\mu$ or $e\mu$);

- at least two jets, with at least one of them being b-tagged, were required;

- in order to avoid the low-mass Drell-Yan background region, events were required to have $m_{\ell\ell} > 15$ GeV;

- in the ee and $\mu\mu$ channels, the missing transverse momentum had to satisfy $E_\mathrm{T}^\mathrm{miss} > 40$ GeV, and the invariant mass of the two leptons had to differ by at least 10 GeV from the Z boson mass, i.e. $|m_{\ell\ell} - m_Z| > 10$ GeV, with $m_Z = 91$ GeV, in order to suppress backgrounds from Z+jets events and events containing misidentified leptons;
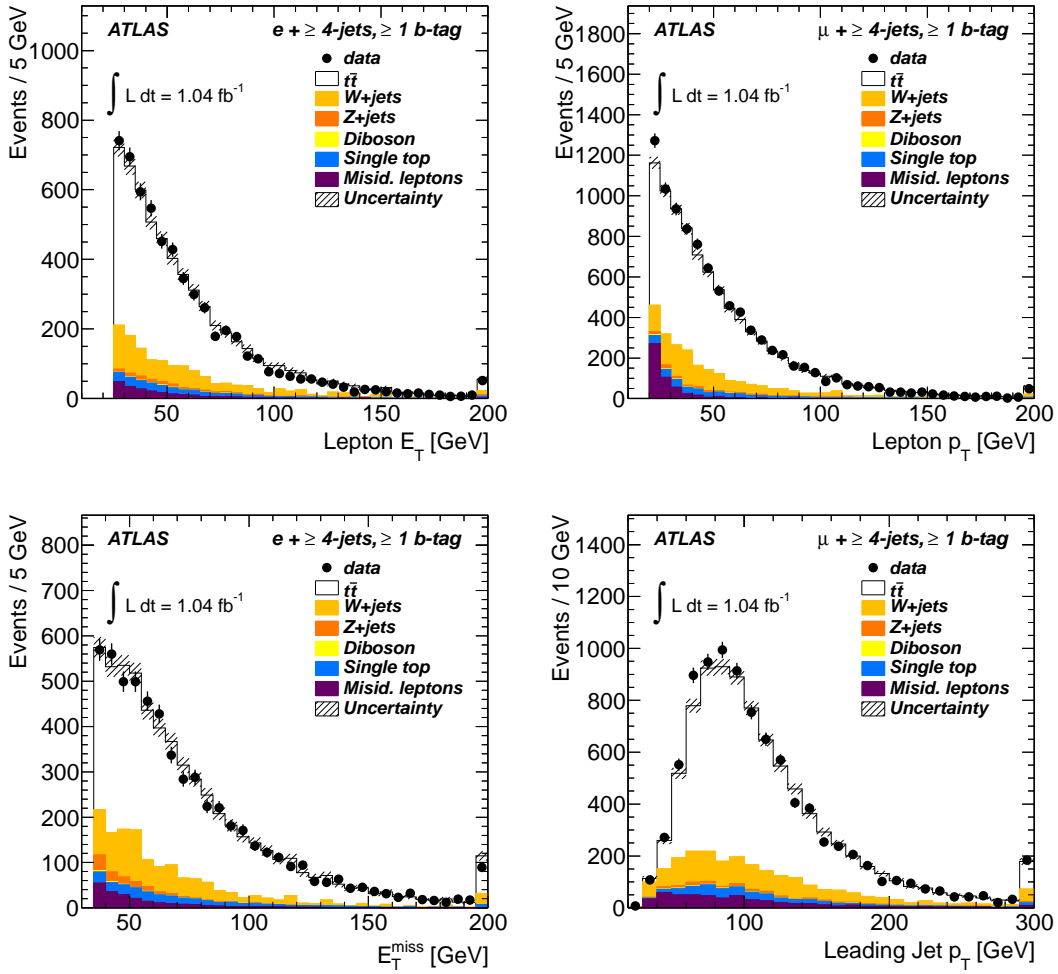
Figure 1. The top row shows (left) the E_T spectrum of the electron in the single-electron channel and (right) the p_T spectrum of the muon in the single-muon channel. The bottom row shows (left) the missing transverse momentum in the single-electron channel and (right) the p_T spectrum of the leading jet in the single-muon channel. The error band shows the statistical uncertainty from the Monte Carlo simulation. The last bin in each distribution includes the overflow.

- in the $e\mu$ channel, no E_T^{miss} or Z boson mass veto cuts were applied; however, the event H_T, defined as the scalar sum of the transverse energies of the two charged leptons and all selected jets, must satisfy $H_T > 130$ GeV to suppress backgrounds from Z+jets production;

- events were required to pass the $t\bar{t}$ reconstruction criteria, as described in Section 4.1.

The numbers of events expected after all selection requirements are shown in Table 2 for the three dilepton channels, together with the observed numbers of events in the data sample. The observed numbers of events is in agreement with those expected, with a purity of 94% for all three channels. The systematic uncertainty discussed in Section 5

Table 2. Event yields in the dilepton channels after the event selection and event reconstruction. The table shows the expected number of events including their estimated total uncertainty as well as the number of events observed in the data sample.

Process	ee channel	$\mu\mu$ channel	$e\mu$ channel
$t\bar{t}$	159 $\pm$ 28	320 $\pm$ 40	750 $\pm$ 100
Z+jets (ee,$\mu\mu$)	0.7 $\pm$ 2.0	2 $\pm$ 4	—
Z+jets ($\tau\tau$)	0.0 $\pm$ 3.8	1.4 $\pm$ 1.3	4.7 $\pm$ 3.1
Diboson	0.2 $\pm$ 0.3	0.6 $\pm$ 0.3	1.3 $\pm$ 0.5
Single top	5.0 $\pm$ 1.3	10.8 $\pm$ 2.4	24 $\pm$ 5
Misidentified leptons	4 $\pm$ 2	7 $\pm$ 4	19 $\pm$ 9
Total predicted	170 $\pm$ 30	340 $\pm$ 40	800 $\pm$ 100
Data	191	354	836

dominates the error on the event yields, with jet energy scale, jet energy resolution, signal and background modelling, and b-tagging being the dominant sources of uncertainty. Example distributions in data are compared with the Standard Model predictions in Figure 2. The data are described well by the expected distributions.

4 Measurement strategies

The two methods to extract the helicity fractions are described below. The analysis was carried out for the single-electron, single-muon, ee, $e\mu$ and $\mu\mu$ channels separately. The reconstruction of $t\bar{t}$ events in the single-lepton channels differs for the two methods: the template method relies more strongly on the structure of the $\cos\theta^*$ distribution than the calculation of the angular asymmetries. It thus relies on an improved estimate of the particle energies. A common reconstruction method was used in the dilepton channels. The results of the analyses and their combination are described in Section 6.

4.1 Measurement using the template method

Templates for different signal and background processes were fitted to the observed $\cos\theta^*$ distributions based on events reconstructed with a kinematic fit in the single-lepton channels [40, 43]. The fit was based on a likelihood which took into account the Breit-Wigner forms of the lineshapes of the top quark and the W boson as well as the energy resolution of the measurements of the jets and the charged leptons. The missing transverse momentum was identified with the x- and y-components of the neutrino momentum. The top quark mass was fixed to 172.5 GeV, and the mass of the W boson was fixed to 80.4 GeV. The likelihood was maximized with respect to the energies of the final state quarks for each association of jets to quarks. The permutations were weighted according to the b-tagging information and the weights were derived from the efficiency and mis-tag rate of the b-tagger. The permutation with the largest value of the likelihood was used in the following steps of the analysis. The overall efficiency for the reconstruction of the correct
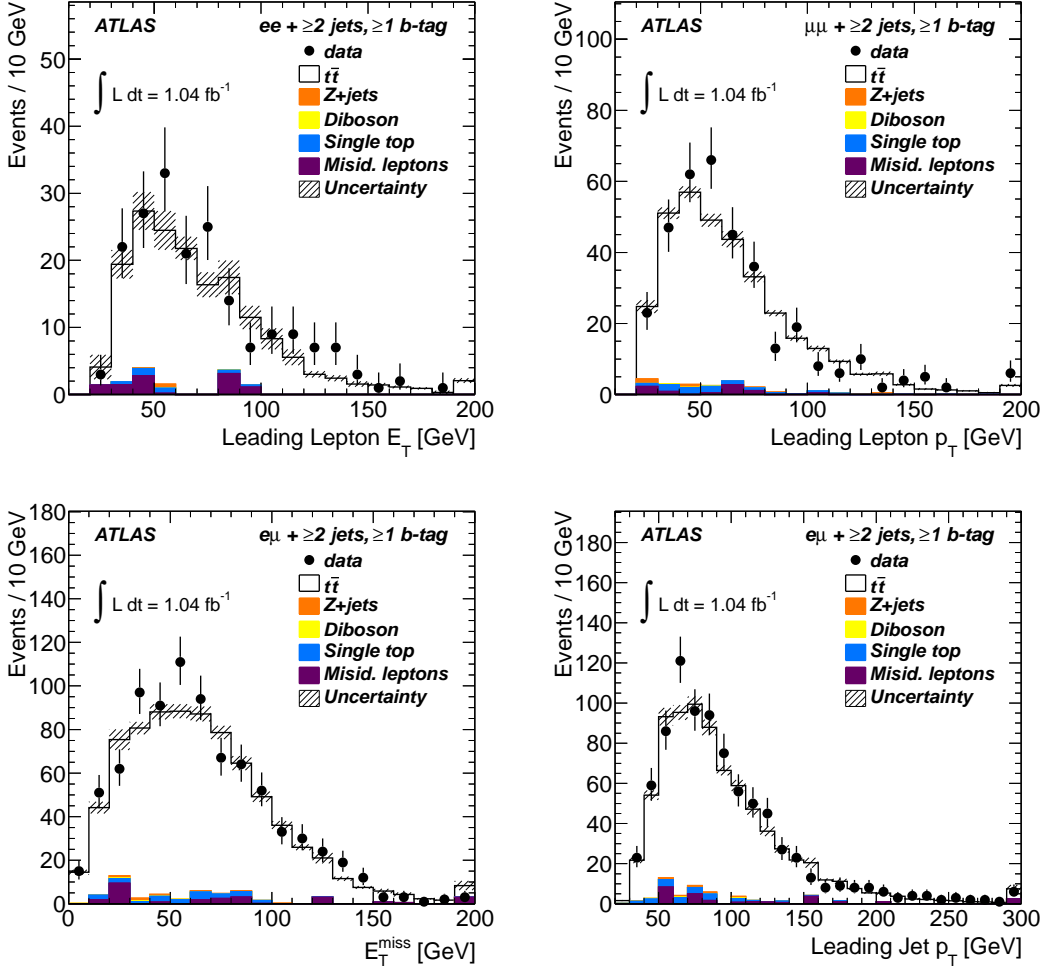
Figure 2. The top row shows (left) the E_T spectrum of the leading electron in the *ee* channel and (right) the p_T spectrum of the leading muon in the $\mu\mu$ channel. The bottom row shows (left) the missing transverse momentum in the $e\mu$ channel and (right) the p_T spectrum of the leading jet in the $e\mu$ channel. The error band shows the statistical uncertainty from the Monte Carlo simulation. The last bin in each distribution includes the overflow.

event topology was found to be 74% in simulated $t\bar{t}$ events. Only those events where four jets and a lepton are matched to partonic particles, corresponding to roughly 30% of the events, were considered for the efficiency computation.

For the dilepton channels, the $t\bar{t}$ system was reconstructed by solving a set of six independent equations:

$$p_x^{\nu_1} + p_x^{\nu_2} = E_x^{\text{miss}};\ \ p_y^{\nu_1} + p_y^{\nu_2} = E_y^{\text{miss}};\ \ (p_{\ell_1} + p_{\nu_1})^2 = m_W^2;$$
$$(p_{\ell_2} + p_{\nu_2})^2 = m_W^2;\ \ (p_{W_1} + p_{j_1})^2 = m_t^2;\ \ (p_{W_2} + p_{j_2})^2 = m_t^2. \tag{4.1}$$

E_x^{miss} and E_y^{miss} represent the x- and y-components of the missing transverse momentum, p_{ℓ_1} and p_{ℓ_2} (p_{j_1} and p_{j_2}, p_{ν_1} and p_{ν_2}) correspond to the four-momenta of the two charged

leptons (jets, neutrinos). Here, m_W and m_t are the W boson and top quark masses, respectively. For events with only one b-tagged jet, this jet and the non-tagged one with the highest p_T were taken as b-jets from the top quark decays. If at least two b-tagged jets are present, the two b-tagged jets with the largest p_T in the event were used. The pairing of the jets with the charged leptons was based on the minimization of the sum of the invariant masses $m_{\ell_1 j_1}$ and $m_{\ell_2 j_2}$. Simulations show that this criterion gives the correct pairing in 68% of the events. Up to four solutions can be found to the Equations 4.1. The solution with the minimum product of neutrino transverse momenta was chosen and is motivated by the low p_T-spectrum of the neutrinos. In case no solution was found, the top quark mass parameter was varied in the 157.5–187.5 GeV range, to try to find one or more solutions. In case a range of top masses provided a solution, that with the top quark mass parameter closest to 172.5 GeV was taken. Again, multiple ambiguities were resolved by taking the solution with the minimum product of neutrino transverse momenta. If still no solution was found, the second pairing of jets and charged leptons was used. If no solution was found after this procedure the event was discarded. This happened in about 25% of the events in data and in simulated $t\bar{t}$ events.

In the single-lepton channels, the following six processes were used as templates: three different helicity state signal processes, the background from events with misidentified leptons, the W+jets contribution and the sum of all other sources of background. The three signal templates were derived from simulation and include single-lepton and dilepton events which pass the event selection. These distributions are shown in Figure 3. The W+jets template was obtained from simulation. The template for events with misidentified leptons was obtained from data. Other processes contributing to the observed spectrum include single top quark, diboson and Z+jets production and were summed in a single template obtained from simulation.

In the dilepton channels, templates for the three different helicity state signal processes were used as well as a single template representing the different background contributions, namely single top quark production, processes with misidentified leptons, production of Z bosons with additional jets and diboson production. All templates were obtained from simulation, except the misidentified leptons template, which was obtained from data.

A binned likelihood fit was used to estimate the expected number of events contributing to the distribution, assuming independent Poisson-distributed fluctuations in each bin. The number of events expected in the ith bin, λ_i, is given as:

$$\lambda_i = \sum_{h=-1,0,+1} \lambda_i^h \cdot \epsilon^h + \sum_{j=1}^{N_{\mathrm{bkg}}} \lambda_i^j, \tag{4.2}$$

where the first term describes the expected number of signal events at particle level with defined helicity h. These are reduced by reconstruction efficiencies and acceptances summarized by the factors ϵ^h estimated from simulation. The second term describes the expected number of events from background processes and N_{bkg} is the number of background templates. The contributions of the various background templates were constrained according to the central values and uncertainties given in Table 1 and Table 2. The uncertainties were assumed to be uncorrelated.
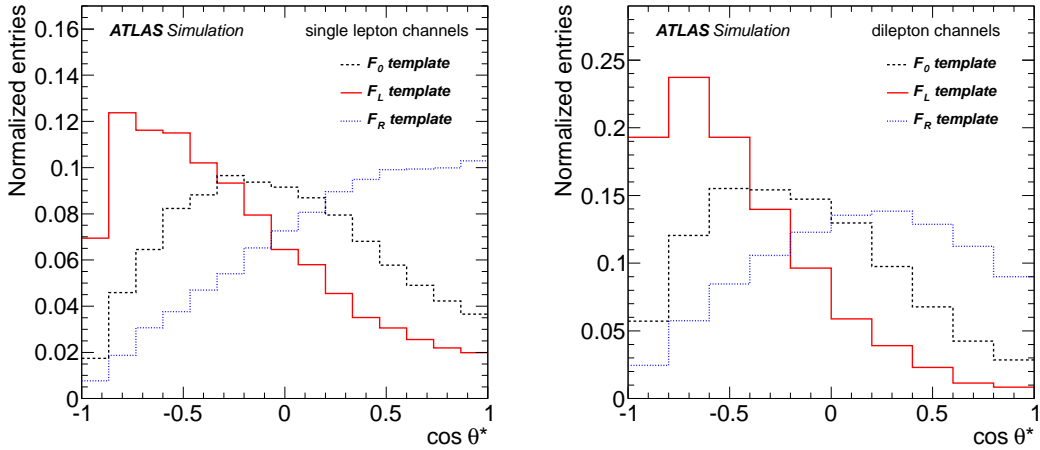
Figure 3. Distributions of $\cos\theta^*$ for each of the three simulated signal templates. The templates for the combined (left) single-lepton and (right) dilepton channels are shown.

4.2 Measurement using the angular asymmetries

The angular asymmetries were measured using the $\cos\theta^*$ distribution obtained by reconstructing the events with a χ^2 minimization technique in the single-lepton channels [44]. The χ^2 was defined according to:

$$\chi^2 = \frac{(m_{\ell\nu j_a} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_b j_c j_d} - m_t)^2}{\sigma_t^2} + \frac{(m_{\ell\nu} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_c j_d} - m_W)^2}{\sigma_W^2} \ , \qquad (4.3)$$

where $m_t = 172.5$ GeV, $m_W = 80.4$ GeV, $\sigma_t = 14$ GeV and $\sigma_W = 10$ GeV are the expected top quark and W boson mass resolutions, ℓ represents the selected electron or muon, $m_{\ell\nu}$ is the invariant mass of the electron (muon) and the neutrino, and $j_{a,b,c,d}$ corresponds to all possible combinations of four jets among all selected jets in the event (with $m_{\ell\nu j_a}$, $m_{j_b j_c j_d}$ and $m_{\ell\nu j_a}$ being the corresponding invariant masses). The neutrino was reconstructed using the missing transverse energy, with the longitudinal component of the neutrino momentum (p_z^ν) allowed to vary. The solution corresponding to the minimum χ^2 value is chosen. No b-tagging information was used in resolving the ambiguities in assigning jets.

The method described in the previous subsection was used to reconstruct dilepton $t\bar{t}$ events.

For the measurement of the angular asymmetries, A_+ and A_-, the $\cos\theta^*$ distribution was divided into four non-uniform bins, which were used to count the number of events above and below $z = \pm(1 - 2^{2/3})$, as defined in Equation 1.2. A background subtraction in the observed $\cos\theta^*$ distribution was performed. Subsequently, the following steps were applied iteratively: the number of reconstructed events above and below $\cos\theta^* = z$ were counted in data for each asymmetry and correction factors were evaluated by comparing the Standard Model expectation with the reconstructed number of simulated $t\bar{t}$ events. These factors allowed corrections to be made for event selection and reconstruction effects. The obtained angular asymmetries were then converted into W boson helicity fractions

and these values were used to re-derive the $\cos\theta^*$ distribution and evaluate new correction factors. The procedure was repeated until the method converged, *i.e.* until the differences between the output observables and the input hypothesis at the previous iteration step were below 0.5%. Closure tests were performed using Monte Carlo samples with different helicity fractions and no bias was observed.

5 Systematic uncertainties

5.1 Sources of systematic uncertainty

Several sources of systematic uncertainty were taken into account in the analyses presented here. These were categorized into the modelling of the signal and background processes, and the detector modelling. The impact of the systematic uncertainties on the final results is summarized in Table 3.

5.1.1 Signal and background modelling

The signal process was modelled with different Monte Carlo generators. Sources of systematic uncertainty considered here were the choice of generator and parton shower model, the choice of parton distribution functions, the assumed top quark mass and the choice of parameters which control the amount of initial and final state radiation. Predictions from the MC@NLO and Powheg generators were compared. The parton showering was tested by comparing two Powheg samples interfaced to Herwig and Pythia, respectively. The amount of initial and final state radiation was varied by modifying parameters in AcerMC interfaced to Pythia. The parameters were varied in a range comparable with those used in the Perugia Soft/Hard tune variations [45]. The impact of the choice of parton distribution functions was studied using the reweighting procedure described in Ref. [44]. MC@NLO samples were generated assuming different top quark masses and their predictions were compared. The observed differences in the results were scaled to variations of 0.9 GeV in the top quark mass according to the uncertainty on its Tevatron average value [3]. The impact of different models of colour reconnection was studied by comparing samples simulated with AcerMC using the Perugia 2010 tune with and without colour reconnection [45] as well as the tune A-Pro and ACR-Pro [46, 47].

Background processes were either modelled by simulation or were estimated in auxiliary measurements. The number of events with misidentified leptons was estimated in data for each channel [40] and the uncertainty on the normalization was estimated to be 50% before and 100% after the b-tagging requirement. The normalization of W+jets processes was estimated from supplementary measurements using the asymmetric production of positively and negatively charged W bosons. The uncertainty was estimated using Berends-Giele-scaling [48] which yielded 48% for events with four jets and increased with the jet multiplicity by 24% per additional jet [39]. Systematic uncertainties on the shapes of the W+jets distributions were assigned based on samples with different simulation parameters such as the minimum transverse momentum of the parton and the functional form of the factorization scale in Alpgen. Scaling factors correcting the fraction of heavy

flavour contributions in simulated W+jets samples were estimated in auxiliary measurements described in Ref. [40]. The uncertainties were 76% for $Wb\bar{b}$+jets and $Wc\bar{c}$+jets contributions, and 35% for Wc+jets contributions. The uncertainty on the normalization of Z+jets events was estimated using Berends-Giele-scaling. The uncertainties in the normalization were 48% for events with four jets and increased with the jet multiplicity by 24% per additional jet. A systematic uncertainty in the shape was accounted for by comparing simulated samples generated with ALPGEN and SHERPA. The uncertainty on the normalization of the small background contributions from single top quark and diboson production was estimated to be about 10% (depending on the channel) and 5%, respectively. The former estimate was based on the difference between the predictions from MC@NLO and MCFM [49], whereas the latter comes from scale and PDF uncertainties evaluated with MCFM.

For the template method, the bin content in each template was varied according to a Poisson distribution to estimate the impact of the finite Monte Carlo sample size used. For the measurement of the angular asymmetries, the $t\bar{t}$ reconstruction parameters were varied. In the single-lepton channels, the top quark and W boson mass resolutions used in the χ^2 definition were changed by 25%. For the dilepton channels, the assumed top quark mass window used in the kinematic equations was reduced by 50%, taking the difference in the observables with respect to the nominal procedure as the uncertainty estimate. The uncertainty due to the finite Monte Carlo sample size was found to be negligible since fewer bins were used in the unfolding than for the templates. These sources of uncertainty are labelled "method-specific uncertainties" in Table 3.

5.1.2 Detector modelling

The mis-modelling of lepton trigger, reconstruction and selection efficiencies in simulation was corrected for by scale factors derived from auxiliary measurements of the processes $Z \to \mu\mu$ and $Z \to ee$ [50, 51]. The uncertainties were evaluated by changing the event selection of the supplementary measurement and by testing the stability of the results against changing LHC and ATLAS run conditions. The same processes were used to measure the lepton momentum scale and resolution. Scale factors and their uncertainties were derived to match the simulation to observed distributions. Details are given in Ref. [39].

The jet energy scale was derived using information from test-beam data, LHC collision data and simulation. Its uncertainty varies between 2.5% and 7% in the central η region, depending on jet p_T and η [52]. This includes uncertainties in the flavour composition of the samples and mis-measurements from close-by jets. An additional p_T-dependent uncertainty of up to 2.5% was assigned to jets matched to b-quarks (using Monte Carlo generator-level information) due to differences between light-quark and gluon jets as opposed to jets containing b-hadrons. Additional uncertainties of up to 5% (8%) in the central (forward) region were added due to pileup. The energy resolution for jets in Monte Carlo simulation was adjusted to that observed in data. Uncertainties on the energy resolution of 4–45%, decreasing with jet p_T, were assigned. The reconstruction efficiency of jets was found to be in good agreement with the predictions from simulation and uncertainties of 1–2% were assigned.

Table 3. Sources of systematic uncertainty and their impact on the measured W boson helicity fractions for the combined single-lepton and dilepton channels. The systematic uncertainties were symmetrized by using the larger uncertainty.

Source	Uncertainties		
	F_0	F_{L}	F_{R}
Signal and background modelling			
Generator choice	0.012	0.009	0.004
ISR/FSR	0.015	0.008	0.007
PDF	0.011	0.006	0.006
Top quark mass	0.016	0.009	0.008
Misidentified leptons	0.020	0.013	0.007
W+jets	0.016	0.008	0.008
Other backgrounds	0.006	0.003	0.003
Method-specific uncertainties	0.031	0.016	0.035
Detector modelling			
Lepton reconstruction	0.013	0.006	0.007
Jet energy scale	0.026	0.014	0.012
Jet reconstruction	0.012	0.005	0.007
b-tagging	0.007	0.003	0.004
Calorimeter readout	0.009	0.005	0.004
Luminosity and pileup	0.009	0.004	0.005
Total systematic uncertainty	0.06	0.03	0.04

The uncertainties on the momenta of electrons, muons and jets were propagated into the missing transverse momentum. A 10% uncertainty from pileup was added in addition.

The b-tagging efficiencies and mis-tag rates have been measured in data [42]. Jet p_{T}-dependent scale factors, applied to simulation to match the data, have uncertainties which range from 9% to 16% and 12% to 45%, respectively.

The uncertainty on the measured luminosity was estimated to be 3.7% [15].

Due to a hardware failure, a small, rectangular region of the ATLAS electromagnetic calorimeter could not be read out in a subset of the data (0.87 fb^{-1}). Data and Monte Carlo events in which a jet or an electron were close to the affected calorimeter region were rejected. The systematic uncertainty labelled "calorimeter readout" in Table 3 was evaluated by varying the criteria to reject these events.

6 Results

The two methods discussed in Section 4 were applied to the data set described in Section 2. Figure 4 shows the observed distribution of $\cos\theta^*$ in the single-lepton and dilepton channels together with the sum of the templates scaled to the best fit parameters obtained from the
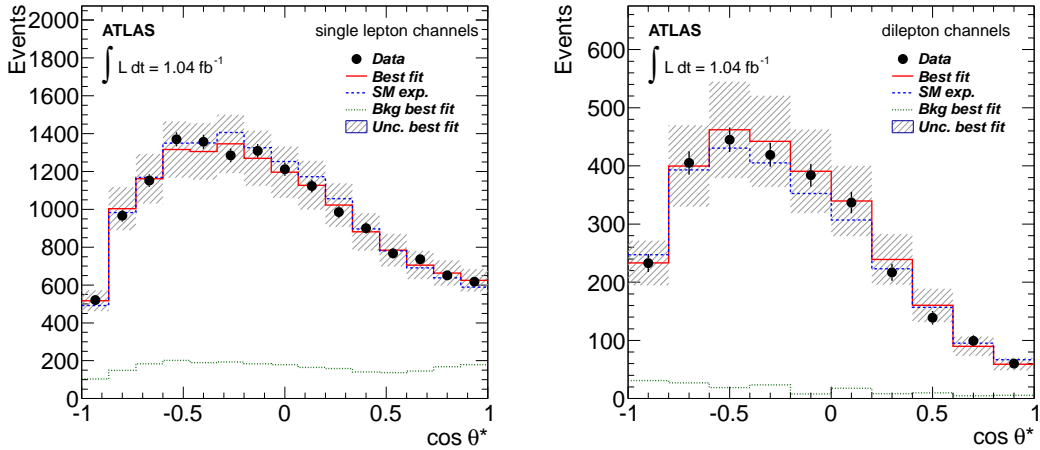
Figure 4. Distributions of the reconstructed $\cos\theta^*$ used in the template method for data (markers), fitted background (dotted line), the Standard Model prediction (dashed line) and the best fit value (solid line) for the (left) single-lepton and (right) dilepton channels. The total uncertainties on the helicity fractions for the best fit values are represented by the grey band. For the dilepton channels, each event contributed with two entries, corresponding to the two leptonic decays of the W bosons.

template method as well as the Standard Model expectations. Figure 5 shows the distribution of $\cos\theta^*$ in the single-lepton and dilepton channels after the background subtraction and the correction for detector and reconstruction effects as used by the asymmetry method as well as the Standard Model expectations.

The combination of the individual measurements of the W boson helicity fractions (F_0 and $F_{\rm L}$) and asymmetries (A_+ and A_-) in the single-lepton and dilepton channels was done using the best linear unbiased estimator (BLUE) method [53, 54]. The impact of the systematic uncertainties described in Section 5 was studied and the results are summarized in Table 4, which also gives the combination of all channels for each method. The results are compatible with each other and with the final combination. In addition, the template fit was repeated with $F_{\rm R}$ fixed to zero[3]. With the precision of the current measurements, this differs negligibly from the Standard Model value, and also follows the approach suggested in Ref [13]. The results can also be found in Table 4.

The results for the angular asymmetries from the single-lepton channels are $A_+ = 0.52 \pm 0.02$ (stat.) ± 0.03 (syst.) and $A_- = -0.84 \pm 0.01$ (stat.) ± 0.02 (syst.) whereas the results for the dilepton channels are $A_+ = 0.56 \pm 0.02$ (stat.) ± 0.04 (syst.) and $A_- = -0.84 \pm 0.02$ (stat.) ± 0.04 (syst.).

Most of the measurements and the combined result are limited by systematic uncertainties. The largest sources of uncertainty are the signal and background modelling, as well as the jet energy scale and jet reconstruction. The template fits are more sensitive

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[3]In the evaluation of the angular asymmetries no assumption is made for the helicity fractions, so it is not possible to fix $F_{\rm R}$ to zero.
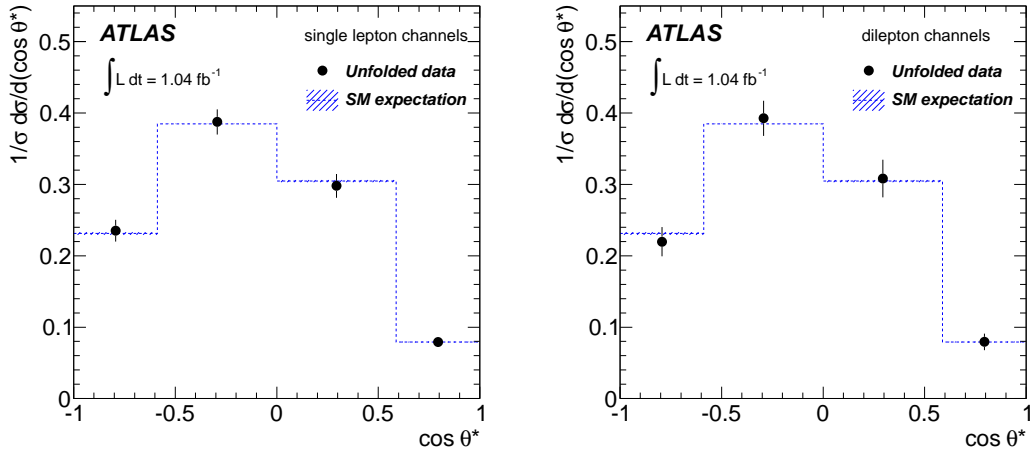
Figure 5. Unfolded distributions of $\cos\theta^*$ for the (left) single-lepton and (right) dilepton channels. The error bars on unfolded data (markers) include both the statistical and systematic contributions. For comparison, the Standard Model NNLO QCD prediction (dashed line) and its uncertainty [4] are also shown.

Table 4. Summary of the W boson helicity fractions measured using the two different techniques described and the combination. The quoted uncertainties are the statistical (first) and the systematic (second) uncertainties.

Channel	F_0	F_{L}	F_{R}
W boson helicity fractions from the template fit			
Single leptons	$0.57 \pm 0.06 \pm 0.09$	$0.37 \pm 0.03 \pm 0.04$	$0.07 \pm 0.03 \pm 0.06$
Dileptons	$0.92 \pm 0.10 \pm 0.10$	$0.17 \pm 0.06 \pm 0.07$	$-0.09 \pm 0.05 \pm 0.06$
Combination	$0.66 \pm 0.06 \pm 0.07$	$0.33 \pm 0.03 \pm 0.03$	$0.01 \pm 0.03 \pm 0.06$
F_{R} fixed	$0.66 \pm 0.03 \pm 0.04$	$0.34 \pm 0.03 \pm 0.04$	0 (fixed)
W boson helicity fractions from the angular asymmetries			
Single leptons	$0.66 \pm 0.03 \pm 0.08$	$0.33 \pm 0.02 \pm 0.05$	$0.01 \pm 0.01 \pm 0.04$
Dileptons	$0.74 \pm 0.06 \pm 0.10$	$0.27 \pm 0.03 \pm 0.05$	$-0.01 \pm 0.03 \pm 0.05$
Combination	$0.67 \pm 0.04 \pm 0.07$	$0.32 \pm 0.02 \pm 0.04$	$0.01 \pm 0.02 \pm 0.04$
Overall combination	$0.67 \pm 0.03 \pm 0.06$	$0.32 \pm 0.02 \pm 0.03$	$0.01 \pm 0.01 \pm 0.04$

to shape-related uncertainties, such as ISR/FSR and jet reconstruction, while the angular asymmetries are more sensitive to background normalization uncertainties, due to the background subtraction which needs to be performed.

6.1 Combination

The results presented in the previous sections were combined using the BLUE method. Both the statistical correlations between analyses, and the correlations of systematic uncer-

tainties, were taken into account. The statistical correlations were estimated to be between 40% and 49% for the single-lepton channels and between 83% and 89% for the dilepton channels using pseudo-experiments obtained from simulated samples. The background-related systematic uncertainties were assumed to be fully correlated within single-lepton channels and within dilepton channels, but uncorrelated between single-lepton and dilepton measurements. The only exception is the uncertainty due to misidentified lepton background which depends on the lepton flavour and thus belongs to the group of lepton-related uncertainties, which were assumed to be fully correlated between the channels with same flavour leptons. The method systematic uncertainties were assumed to be uncorrelated between channels and the remaining sources of systematic uncertainty were assumed to be fully correlated between channels. Various tests were performed in which the correlations among the sources of systematic uncertainty were varied. It was found that the values assumed for the correlations were conservative. The systematic uncertainties on the combined values are summarized in Table 3. The four measurements of the helicity fractions and the combined values are shown in Table 4 and Figure 6.

The individual measurements agree reasonably well within their total uncertainties. The χ^2/dof for the global combination of the template fit and asymmetries measurements was 0.8 with a χ^2-probability of 75%, where dof is the number of degrees of freedom. The largest difference between two measurements is that between the single-lepton and dilepton channels obtained with the template method. Since the measurements were performed in five independent channels (single electron, single muon, ee, $e\mu$ and $\mu\mu$), the combination was performed based on the five individual measurements taking into account all correlations. The χ^2/dof calculated using the BLUE method for this combination was 1.3 with a χ^2-probability of 23%.

The combined W boson helicity fractions are:

$$F_0 = 0.67 \pm 0.03 \text{ (stat.)} \pm 0.06 \text{ (syst.)}\,,$$
$$F_\mathrm{L} = 0.32 \pm 0.02 \text{ (stat.)} \pm 0.03 \text{ (syst.)}\,,$$
$$F_\mathrm{R} = 0.01 \pm 0.01 \text{ (stat.)} \pm 0.04 \text{ (syst.)}\,.$$

The correlation coefficient between F_0 and F_L was estimated to be -0.96. For completeness, these results can be translated into angular asymmetries, yielding $A_+ = 0.53 \pm 0.02$ and $A_- = -0.84 \pm 0.02$.

An alternative analysis, based on requiring two b-tagged jets to further suppress the W+jets background and events with misidentified leptons, was used to measure the helicity fractions in the single-lepton channels as a cross-check. The observed $\cos\theta^*$ distributions were corrected by subtracting the expected background contributions and were unfolded using correction functions in an iterative method similar to the one used in the measurement of the angular asymmetries described in Section 4.2. The results were found to be in agreement with the single-lepton measurements presented in this paper.

6.2 Constraints on the Wtb vertex structure

Any deviation of F_0, F_L, F_R (or A_+ and A_-) from the Standard Model prediction could be caused by new physics contributing to the Wtb vertex. Such new interactions associated
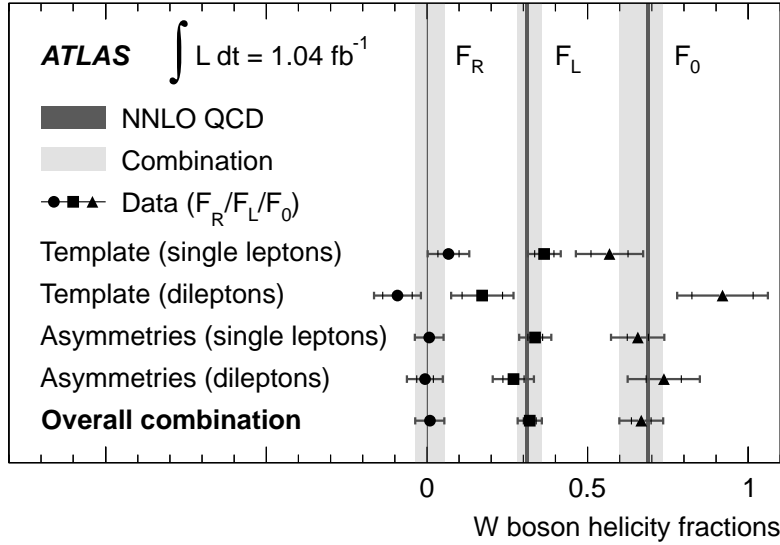
Figure 6. Overview of the four measurements of the W boson helicity fractions and the combined values. The error bars correspond to the statistical and total uncertainties.

with the top quark may exist at higher energies. New physics can be parameterized in terms of an effective Lagrangian [11] above the electroweak symmetry breaking scale of $v = 246$ GeV. After electroweak symmetry breaking, the Wtb Lagrangian [12, 55] is:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)t\,W_{\mu}^{-} + \text{h.c.}\,, \quad (6.1)$$

where P_{L} (P_{R}) is the left-handed (right-handed) chirality operator and

$$V_{\mathrm{L}} = V_{tb} + C_{\phi q}^{(3,3+3)}\frac{v^2}{\Lambda^2}\,, \quad V_{\mathrm{R}} = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2}\,, \quad g_{\mathrm{L}} = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}\,, \quad g_{\mathrm{R}} = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}\,. \quad (6.2)$$

The parameter Λ is the new physics scale and $C_{\phi q}^{(3,3+3)}$, $C_{\phi\phi}^{33*}$, C_{dW}^{33*} and C_{uW}^{33} are the effective operator coefficients [13, 55]. The anomalous couplings V_{R}, g_{L}, g_{R}, generated by dimension-six operators, are absent in the Standard Model at tree level, while the coupling V_{tb} receives a correction from the operator $O_{\phi q}^{(3,3+3)}$.

Limits on anomalous couplings (V_{R}, g_{L} and g_{R}) were obtained from the combined measurement of the W boson helicity fractions by exploiting their dependence on these couplings, as implemented in the TopFit program [10, 56] and normalizing to $V_{\mathrm{L}} = 1$. The allowed regions of (g_{L}, g_{R}) are shown in Figure 7, assuming $V_{\mathrm{R}} = 0$. The upper disconnected region in the plot shows a large-g_{R} second solution to the quadratic equation relating the observables to the anomalous couplings. However, this region is disfavored by the measured cross-section for single top production at the Tevatron [17, 57, 58].

In addition to this two-dimensional limit it is useful to set limits on single anomalous couplings, taking only one of them non-zero at a time. These are, at 95% confidence level,
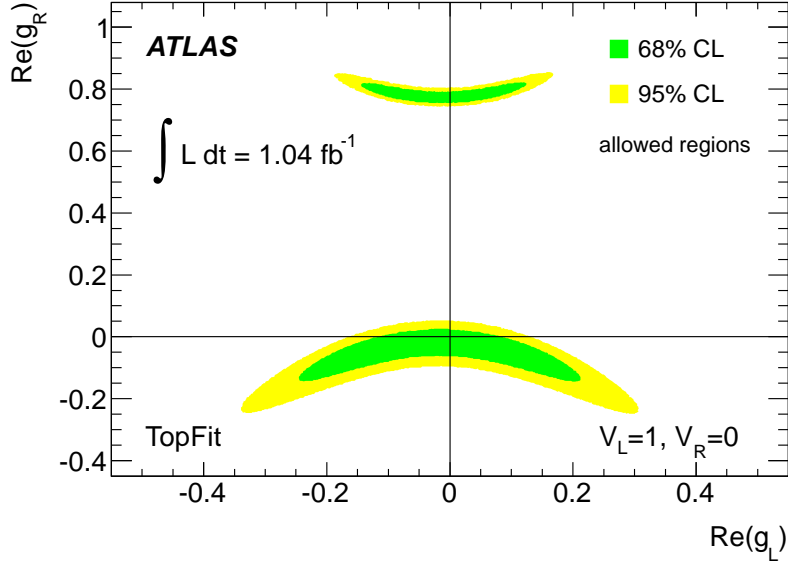
Figure 7. Allowed regions at 68% and 95% confidence level (CL) for the Wtb anomalous couplings g_L and g_R. In the Standard Model, the anomalous couplings vanish at tree level [59].

$$\mathrm{Re}\,(V_{\mathrm{R}}) \in [-0.20, 0.23] \rightarrow \frac{\mathrm{Re}\,(C_{\phi\phi}^{33})}{\Lambda^2} \in [-6.7, 7.8] \ \ \mathrm{TeV}^{-2}\,,$$

$$\mathrm{Re}\,(g_{\mathrm{L}}) \in [-0.14, 0.11] \rightarrow \frac{\mathrm{Re}\,(C_{dW}^{33})}{\Lambda^2} \in [-1.6, 1.2] \ \ \mathrm{TeV}^{-2}\,,$$

$$\mathrm{Re}\,(g_{\mathrm{R}}) \in [-0.08, 0.04] \rightarrow \frac{\mathrm{Re}\,(C_{uW}^{33})}{\Lambda^2} \in [-1.0, 0.5] \ \ \mathrm{TeV}^{-2}\,.$$

The considered W boson helicity observables also allow a second region for g_{R} when the remaining anomalous couplings vanish: $\mathrm{Re}\,(g_{\mathrm{R}}) \in [0.75, 0.80]$ at 95% confidence level. It should be noticed, however, that such large coupling values would imply a single top production cross-section value disfavored by the Tevatron measurements [17, 57, 58]. Using a Bayesian approach [60], the measurement of the W boson helicity fractions with F_{R} fixed at zero, was translated into a 95% probability interval on $\mathrm{Re}\,(C_{uW}^{33})/\Lambda^2$, as proposed in Ref.[13]. This interval was found to be $[-0.9, 2.3]$ TeV^{-2}.

It can be seen that the limits on C_{dW}^{33} (mediating the production of right-handed b-quarks in the top decay) are of the same order of magnitude as the limits on C_{uW}^{33} (involving left-handed quarks). This reflects a good sensitivity to the effective operator corresponding to C_{dW}^{33}, even if its contribution is suppressed by $1/\Lambda^2$ instead of $1/\Lambda$ [61].

These limits are more stringent than those obtained by the DØ Collaboration [58, 62][4]. Indirect, model-dependent limits on the anomalous couplings have been inferred from measurements of radiative B-meson decays, measurements of $B\bar{B}$-mixing and electroweak

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[4]The limits from the DØ Collaboration were derived assuming a massless b-quark.

precision data [63–67], but these limits include assumptions on the absence of additional new physics effects that are not needed in this analysis.

7 Conclusions

A measurement of the polarization of the W bosons in top quark decays was presented, based on 1.04 fb^{-1} of data collected with the ATLAS detector in 2011. The single-lepton and dilepton decay topologies of top quark pairs were considered in the analysis.

The helicity fractions obtained from a combination of template fits to the reconstructed $\cos\theta^*$ distributions and angular asymmetries calculated from the unfolded $\cos\theta^*$ distributions are $F_0 = 0.67 \pm 0.07$, $F_{\mathrm{L}} = 0.32 \pm 0.04$ and $F_{\mathrm{R}} = 0.01 \pm 0.05$. These results are in agreement with NNLO QCD predictions and are more precise than previous results obtained by the CDF and DØ Collaborations [6–8].

Limits on the Wtb vertex anomalous couplings were obtained from the combined results on the W boson helicity fractions. These results are consistent with the $(V - A)$ structure of the Wtb vertex and improve on the previously obtained limits [58].

8 Acknowledgements

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